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## **Recent sedimentation and stratigraphic development in the Arabian Gulf**

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### **LONG TERM GOALS**

The Arabian Gulf is a shallow (<100 m), epicontinental sea connected to the Gulf of Oman through the Straits of Hormuz. This basin, besides being an important military, economic, and political region, serves as an excellent model for sequence stratigraphic studies of an arid littoral environment. Neogene sediments in the Gulf comprise a northeastward-thickening wedge (0.1-2.0 km) of clastics shed from the Zagros uplift in Iran. Our long-term goal is to understand how variations in sediment source, tectonic subsidence, climate, and sea level affected sedimentary processes and stratigraphic development of an arid, shallow-marine environment.

### **OBJECTIVES**

The Persian/Arabian Gulf is subsiding in response to the collision between the Arabian and Asian plates and to growth during the last 5-10 Myrs of the Zagros mountains. Uplifted foldbelts, thickened continental crust, and poorly understood subcrustal loads depress the northeast edge of the Arabian plate creating, by lithospheric plate flexure, a foreland basin that is filled to the southeast with the shallow Gulf sea and to the northwest with sediment deposited by the Mesopotamian river system. The stratigraphy of Neogene sediments within the Gulf is clearly affected by the tectonics of the collision and mountain building.

Our previous studies of sediment cores and echo-sounding profiles in the Arabian Gulf revealed an unconformity dating to the Last Glacial Maximum (LGM) and a sequence of deltas along the northern Iranian margin (Uchupi et al., 1996, 1998). Radiocarbon ages suggested that the basin was subsiding in apparent contradiction to previous interpretations of seafloor topography (eg. Kassler, 1973). In the initial part of the present study, our objective was to test the hypothesis that the Iranian (NW) side of the basin is subsiding more rapidly than the Arabian side to the southwest.

Our early studies of seismic reflection profiles in the Arabian Gulf revealed an unconformity dipping to the northeast towards Iran (Ross et al., 1986). This unconformity was interpreted to be the base of the foreland basin sediment sequence shed from the rising Zagros range. Our second objective was to understand how tectonics of collisional plate boundaries and deformation of continental crust controls the stratigraphic development of these sediments and, thus, their physical properties.

### **APPROACH**

In July-August 1998 aboard the *USNS Bowditch*, we collected sediment cores, CTDs and XBTs, sonobuoy refraction profiles, and high-resolution seismic profiles obtained with the ship's 3.5 kHz echosounding transducer and a towed 48-channel reflection system. This survey covered as much of the Gulf as possible given the restrictions that reefs, oil fields and territorial limits have on operations of NAVOCEANO ships. The approach was to use seismic profiles to map Neogene stratigraphy and to tie this structure to dated surface sediment cores and industry wells where possible. The survey was a joint program between WHOI and NAVOCEANO.

Our approach was to map Neogene stratigraphy with echo-sounding and seismic reflection profiles collected on the *Bowditch* and earlier cruises to the Gulf and to tie this structure to lithology and dates from sediment cores and industry wells where possible. To address our first objectives, we mapped the LGM unconformity and the overlying Holocene unit, mapped channels in the LGM surface beneath the soft delta marls, tracing these features into the deeper regions of the basin, and using the topography of the seafloor and the LGM surface to try to explain the geometry and nature of the foreland basin unit. To address our second objective, our approach was to map Neogene stratigraphy with seismic reflection profiles and tie this structure to lithology and dates from industry wells where possible. To try to explain the geometry and nature of the foreland basin unit, most of our effort was put into a study of the neotectonics of the Zagros to determine how lateral variations along the range affected patterns of sediment supply to the basin and the tectonic component of subsidence.

## WORK COMPLETED

In the first year, we compiled, edited, and mapped the primary seafloor structures in water depths greater than ~30 m (Figure 1b). These data were merged with soundings on navigation charts to produce a digital data base for the Gulf as a whole (Figure 2a). We examined all 3.5 kHz records from both the July and August 1998 legs of the *USNS Bowditch*, identified and digitized the LGM surface (identified here as Horizon 1), and produced a structural map of the surface (Fig. 1a) and an isopach map of the overlying Holocene unit (Fig. 1b).

In the second year we interpreted the MCS profiles from the 1998 *USNS Bowditch* cruise. We integrated these results with those from our interpretation of 1977 *R/V Atlantis II* reflection records and industry profiles and tied the seismics to the few industry wells for which we had geologic data (Swift et al., 1998). We used an average velocity-depth function from well check-shot surveys to compute sediment thickness. We prepared maps of depth to the youngest horizons that can be correlated throughout the basin. These horizons precede the initiation of mountain building by 6-10 Ma, but the intervening sediment units are relatively thin. So, the horizons provide a good marker for the start of foreland basin subsidence. No reflections in the overlying basin sequence can be traced laterally for more than 50-100 km and, thus, can not be mapped with our line spacing. Lateral variations along the Zagros were studied by defining tracks perpendicular to the range and foreland basin and extracting topographic size, shape, and location parameters from a data base that included the USGS 30 sec land elevation compilation and water depths from several sources. Geophysical data included gravity data from BGI in Paris and earthquake hypocenters from the Iris ISC catalog and smaller, more-reliable relocations done by Engdahl, Maggi, and others. Maps of geothermal gradient were obtained from Iran. Published seismic surveys in Iran and Iraq and geologic descriptions from industry maps and published literature were compiled.

## RESULTS

### Holocene erosion and sedimentation

The most startling result is the apparent lack of Holocene sediment over most areas of the Gulf deeper than ~30 m (Figure 1a). Sediment cores confirm this result. Sediment cores in regions with 0-2 m of Holocene material identifiable in the acoustic records often penetrate 10-50 cm of Holocene marl into reddish-brown Pleistocene sediment. Holocene accumulation is constrained to the margins of the basin off rivers draining the Zagros Mountains in Iran and to small, thin regions of presumably carbonate deposition in 40-50 m of water off UAE (54°45' W and 55°30' W). Few data were collected close enough to Iran's coast to adequately map the Holocene unit, so the extent of its distribution is under-represented in Figure 1b. The Tigris-Euphrates-Karun Delta in the northwest portion of the Gulf is problematic. Although, the delta is commonly interpreted as a Holocene feature, we could not identify Holocene material acoustically (Figure 1b). Sediment cores closest to this delta recovered a layer of marl <1 m thick above cross-bedded reddish-brown sand.

Surface textures of quartz grains suggest aeolian processes deposited the sand. We have not yet dated this material, so the accuracy of our seismic interpretations at the northwest end of the Gulf can not be confirmed.

The shape of the LGM surface in the northern basin (northwest of the sill at  $\sim 52^\circ$  W) differs significantly from that of the central basin to the southeast (Figure 1a). The surface is very flat on transects from southwest to northeast - increasing in depth by 20 m from  $\sim 55$  m to  $\sim 75$  m. The SW-NE lateral gradients are much greater in the central basin where depths reach over 100 m. The lateral gradients in the other direction also differ. Depth to the LGM in the northern basin increases systematically from  $\sim 40$  m off the Hilleh River to  $\sim 75$  m at the sill ( $52^\circ$ W), whereas depth does not appear to systematically vary along the central basin. The origin of these differences is unclear because many processes can affect seafloor depth in epi-continental seas, but our preferred interpretation is that subsidence rate increases much more in a SW-NE direction across the central basin than across the northern basin. In this respect, the central basin appears to follow the pattern predicted by foreland basin models. Radiometric dates on sediment cores from the northern basin indicate subsidence (Uchupi et al., 1998), but the rates may be less than those in the central basin reflecting, perhaps, NW-SE lateral differences in deformation within the Zagros Mountains.

Our present data suggest that channels eroded in the LGM surface are found, for the most part, only beneath the Holocene deltas off Iranian rivers (Figure 2). Figure 3c shows an example. They appear to develop in Pleistocene delta marls that are probably softer than older, coarser, and more consolidated sediment exposed along the southwest side of the Gulf. The channels are "perched" on the Iranian margin and cannot be traced either as fans or channels onto the floor of the northern basin. The channels terminate where the Horizon 1 surface abruptly steepens down to what appears to be a wave-cut terrace at 75-78 m (Figures 3a, 3c, and 3). In the northern basin the terrace extends for 50-60 km southwestward across the floor of the basin (Figure 1a) and appears to represent a still-stand in relative sealevel. The terrace can be traced around the southeast nose of the delta ( $\sim 52^\circ$ W) and northward into the central basin at a depth of  $\sim 85$  m. Based on these depths, we estimate differential subsidence of about 0.6 mm/yr. We tentatively date the terrace and the channels to the end of the Younger Dryas at  $\sim 11,500$  yrs BP. Future radiocarbon dates on sediment cores will help to constrain our chronology.

#### Development of the foreland basin

Most sediments down to 0.6-1.2 km depth beneath the Gulf are comprised of shallow marine sands and marls thickening northeastward towards Iran. The seismic section in Figure 4a shows a prominent reflection/unconformity, dipping from 0.2 sec on the southwest to 1.1 sec on the northeast, that correlates in one well to the top of the Asmari limestone with age of Early Miocene. The horizon appears to be time-transgressive, because the reflection elsewhere appears to represent the top of Lower Fars units (anhydrite, salt, shale, or carbonate beds) that were deposited in middle and early-late Miocene. Underlying reflections correlate to carbonate units deposited during stable epi-continental sea conditions. The overlying wedge unit is comprised primarily of units with poor lateral correlation that thin to the southwest. In general, these sediments are finer-grained and include more terrigenous clastic material than the pre-Asmari sequence. Accumulation rates are much higher. As a result, seismic velocities beneath the Gulf decrease towards the northeast (Figure 4b). Throughout the Gulf the base of the foreland basin sedimentary unit dips down towards the northeast (Figure 5). Tectonic depression of the crust beneath the Gulf, however, has not been uniform during the last 5-10 Ma: the dip of the reflector and the thickness of the wedge near the Iranian coast increase northwestward. This trend is a result of variations in style of deformation in the Zagros range.

In general, structural features in the Zagros trend NW-SE parallel to the plate suture zone. This trend is broken by two embayments of lower topography that, not coincidentally, include the bulk of the Iraqi and Iranian oil reserves. The origin of these embayments and their implications for subsidence in the Gulf were poorly resolved prior to this investigation. These features have been attributed to syntaxies in plate convergence and to locations where the absence of a salt layer overlying basement reduced folding.

Our mapping suggests that the deformation of the Zagros (and, as a result, the structural and stratigraphic history of deposits in the foreland basin) are controlled by processes of crustal shortening deep within continental crust. Variations in the width of the foreland basin (ie. the Gulf) do not correlate with the cross-sectional area or width of the Zagros range. We infer that the width of the basin depends on the deep structure of the Arabian plate boundary beneath the suture zone that can not be resolved with present data. In contrast, the thickness of the basin fill appears to be controlled by patterns of crustal deformation. All earthquakes occur within continental crust, and their distribution parallels topography, ie. there are few earthquakes in the lowlands of the topographic embayments. Horizons within the Gulf and Mesopotamian plain deepen adjacent to the embayments and shallow in front of the intervening foldbelts, but there is no corresponding change in the width of the foreland basin. This lack of correlation indicates that basement subsidence is not a simple function of loading and flexure of the plate edge. The dichotomy in topographic profiles between embayments and foldbelts can be correlated to profiles created when the crustal shortening is modeled with and without a low viscosity layer in the lower crust (Royden, 1996). The observed lateral variability in topography of the Zagros range - and, thus, the stratigraphic development within the foreland basin - developed in response to variations in lower crustal rheology with lateral scales of 300-400 km.

### **IMPACT/APPLICATIONS**

Channels buried beneath the acoustically transparent marl deltas along the Iranian coast do not appear to be constrained to the mouths of present rivers. They occur along the crest of the preceding paleo-delta and terminate abruptly along the steep, wave-eroded slope bordering the northern basin terrace. The channels do not extend more than a few hundred meters out onto the floor of the Gulf. Lateral variations in subsidence rate do not agree with simple foreland basin models and appear to be a primary agent controlling patterns of sediment accumulation.

Foreland basin tectonics controls the nature of Gulf sediment and its accumulation rate. These in turn control the physical and acoustic properties of the seafloor and the upper 1-2 km of sediment (eg. Figure 5). Propagation of low-frequency sound in the upper 1 km beneath the Gulf is slower near Iran than near Arabia, and this affect is more pronounced closer to Iraq. Scientifically, we show that inhomogeneities in lower continental crust rheology affect subsidence in a foreland basin and, thus, basin stratigraphy. It is possible that similar inhomogeneities occur elsewhere along the edges of continents and affect sediment patterns on continental shelves and slopes.

### **TRANSITIONS**

These results - and others that we prepare as we progress with this project - will be transitioned to our colleagues at NAVOCEANO for their use in preparation of data bases in support of fleet operations.

### **RELATED PRODUCTS**

The high-resolution seismic and seafloor mapping results provide an arid environment end-member to the STARTIFORM field studies.

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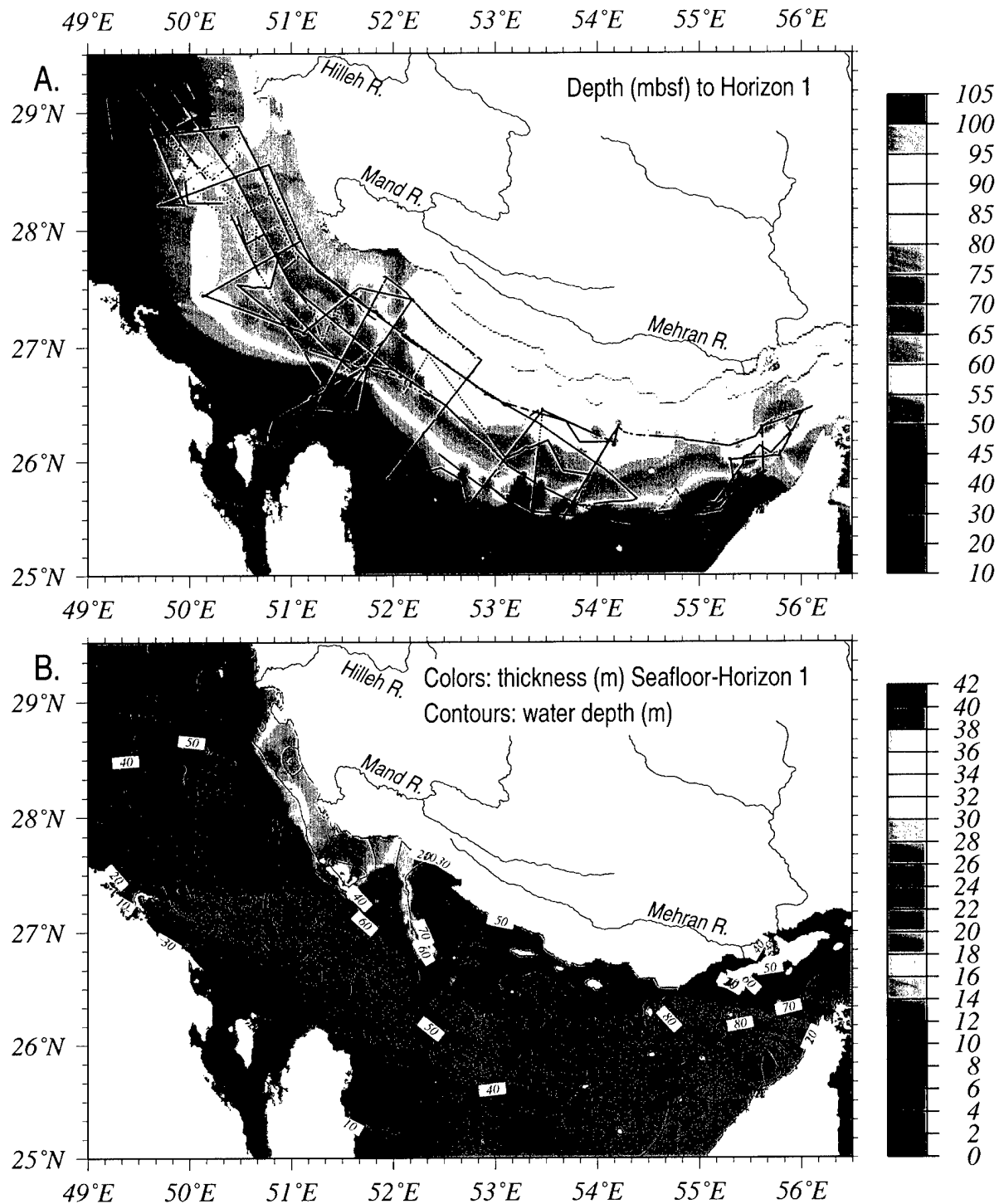


Figure 1. (a) Structure map on Horizon 1 shows the depth below sealevel to the LGM unconformity. Black dots indicate the distribution of data points from the 3.5kHz data collected on the USNS Bowditch in 1998. (b) Thickness of the interval between the seafloor and Horizon 1. This unit is primarily marls deposited in late Holocene deltas seaward of rivers draining the Zagros Mountains in Iran. Contours are depth to seafloor based on only the bathymetry data collected along the tracklines shown in (a).

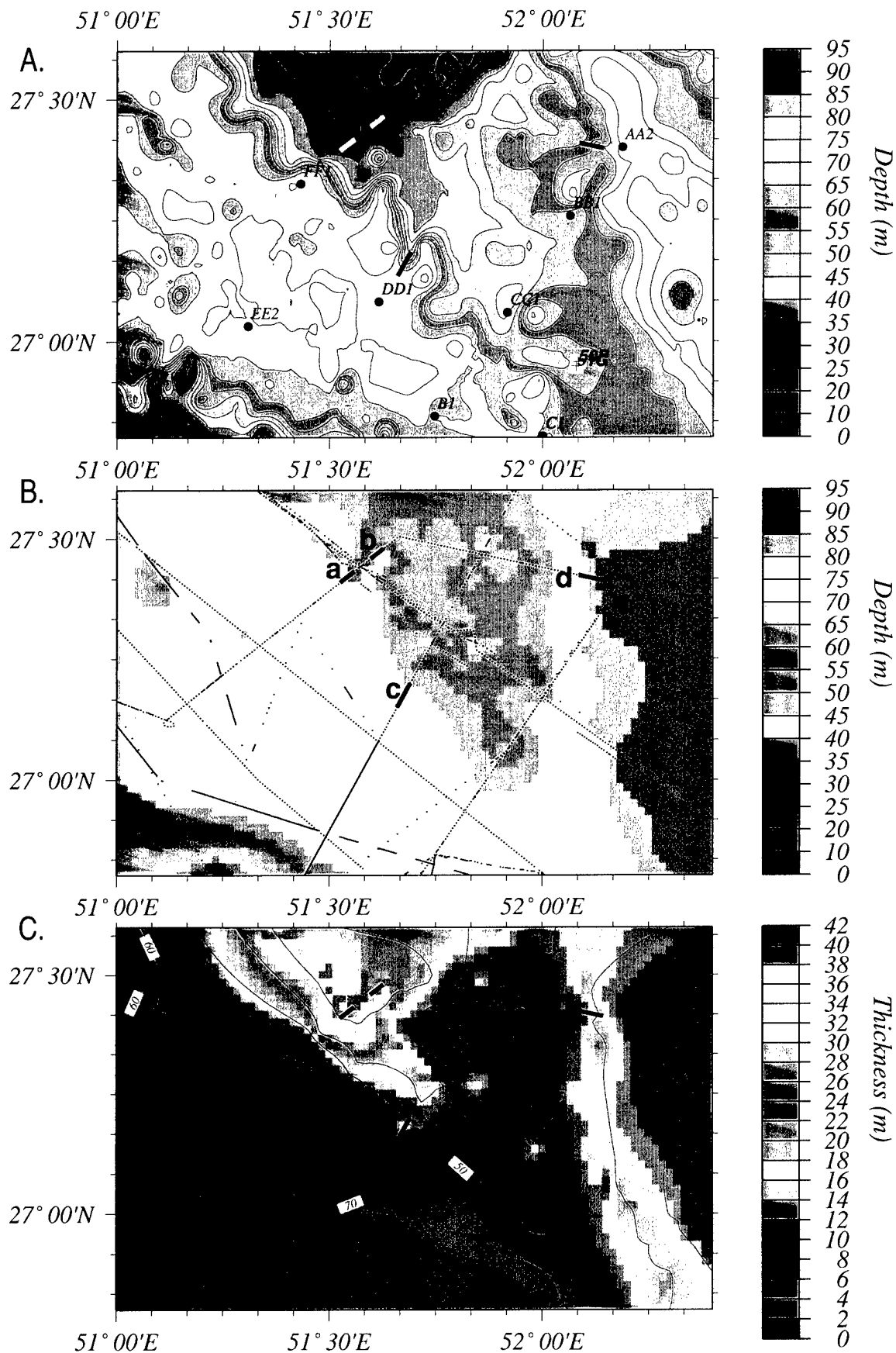
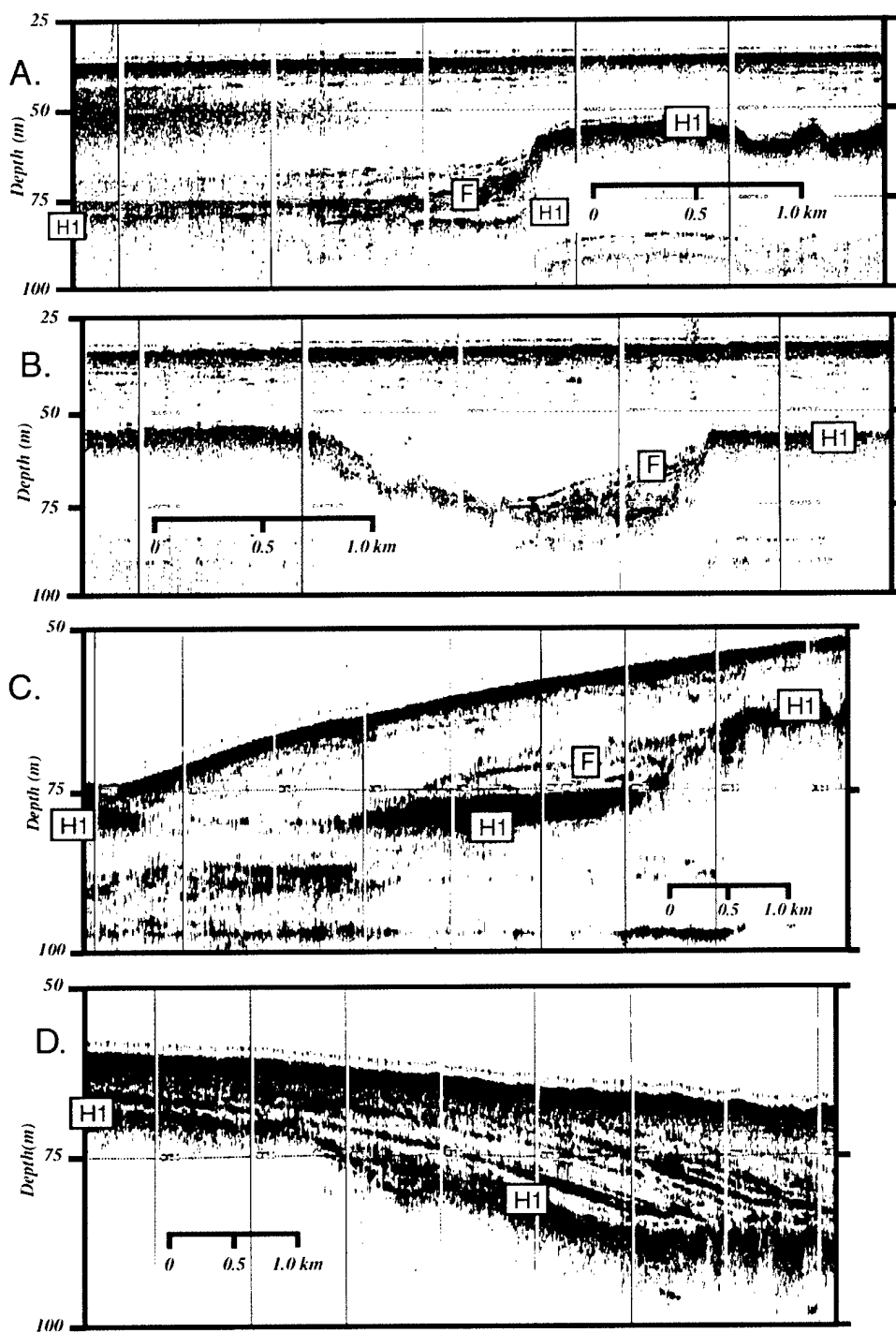


Figure 2. Detail of Arabian Gulf shows the southeast tip of the Iranian river deltas. (a) Bathymetry based on soundings digitized from navigation charts. Black dots indicate locations of sediment cores. (b) Depth to Horizon 1 (same as Figure 1a). Black lines indicate data base used for contouring (b) and (c). Letters indicate locations of profiles in Figure 3. (c) Thickness of the interval between the seafloor and Horizon 1 (same as Figure 1b).





**Figure 3.** Subbottom profiles (hull mounted 3.5 kHz) showing a fluvial channel (b) buried beneath Holocene marl and abrupt steepening of the Horizon 1 (H1) surface along the edge of the underlying delta deposits (a, c, and d). "F" indicates fluvial sediments filling the channel and bounding the scarp. In (d) reflectors within the Holocene unit downlap onto Horizon 1 towards the west into the central basin. Locations are shown in Figure 2b.

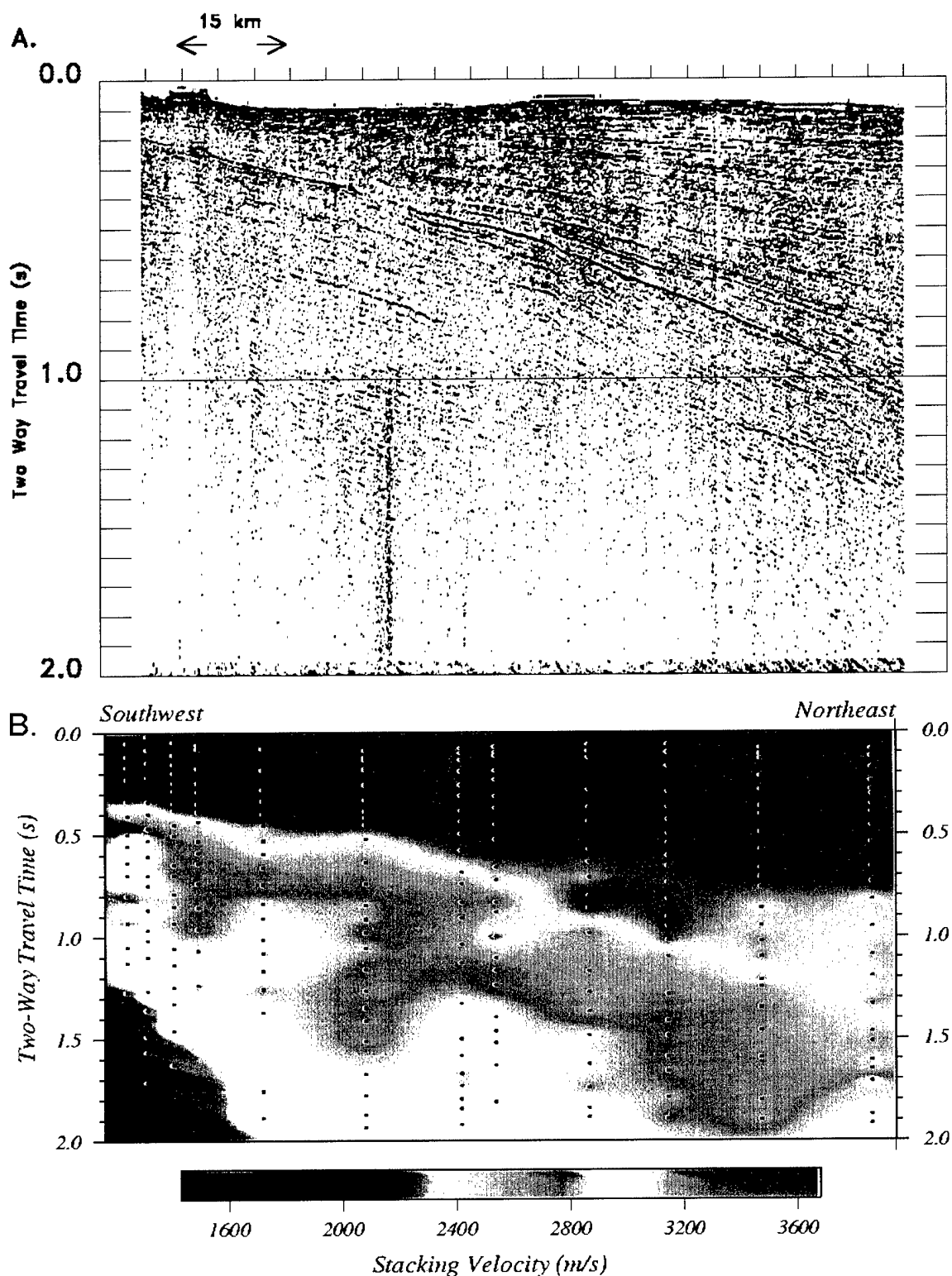


Figure 4. Foreland basin sediments, with low seismic velocities, increase in thickness from ~0.2 km off Arabia to ~1 km off Iran. (a) Seismic profile extends northeastward from the edge of carbonate bank off Qatar to within ~15 km off Iran. (b) Stacking velocities computed during MCS processing (dots) are up to 0.5 km/s slower in the foreland basin wedge.

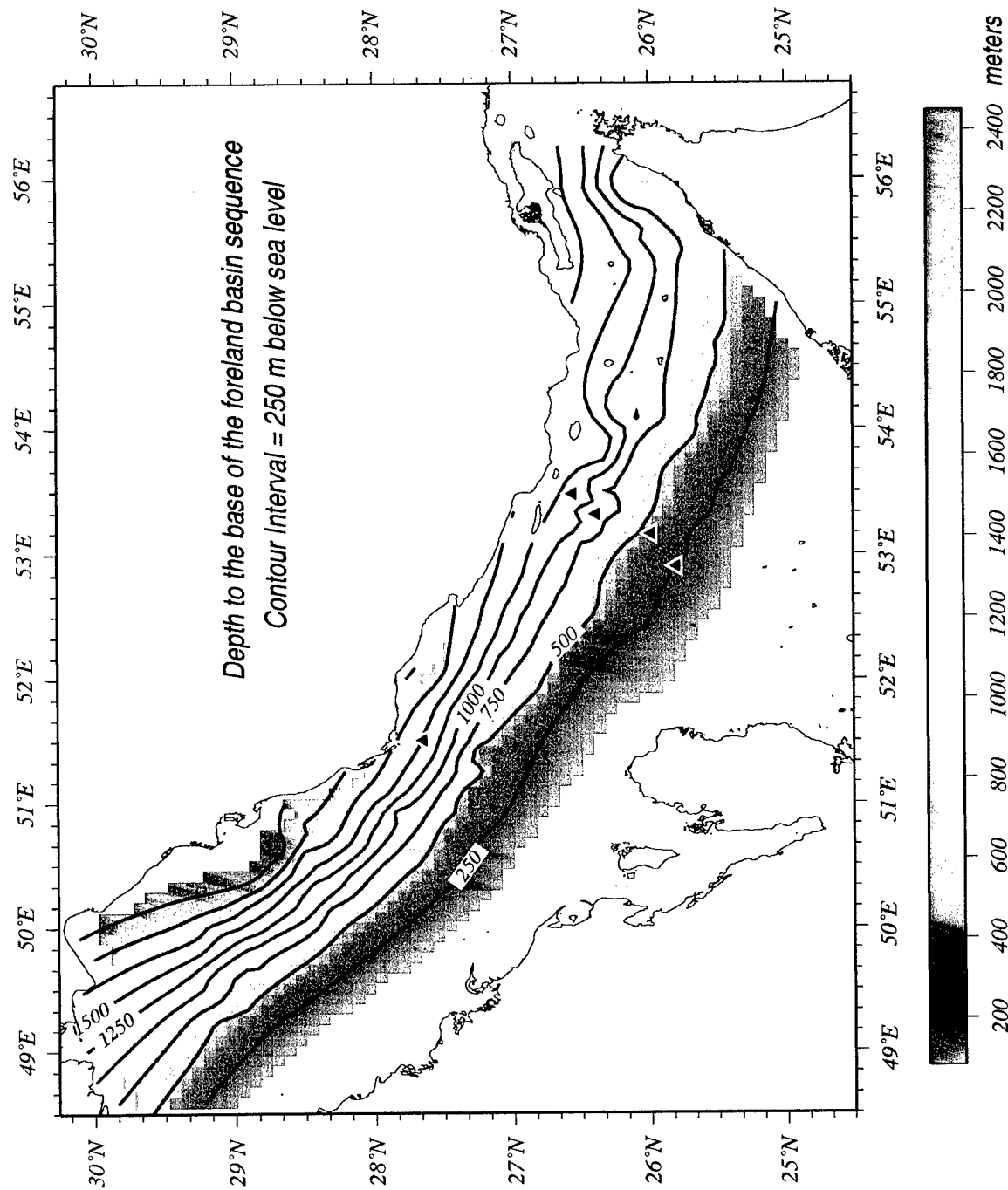


Figure 5. The base of the foreland basin wedge dips northeastward from about 100 m below sea level off Arabia. The depth to the base of the wedge off Iran increases from about 1250 m near Laven Island (53.2E, 26.8N) in the southeastern portion of the Gulf to 2250-2500 m off Kharg Island in the northwestern Gulf. Depths were compiled from seismic reflection surveys. Triangles indicate locations of five industry wells to which we could tie the mapped horizon and obtain geologic control. Increase in dip towards the northwest reflects a change in the nature of deformation process in the lower continental crust due to the Zagros continental collision.